

Greater than 20%-efficient frequency doubling of 1532-nm nanosecond pulses in quasi-phase-matched germanosilicate optical fibers

V. Pruneri, G. Bonfrate, P. G. Kazansky, D. J. Richardson, N. G. Broderick, and J. P. de Sandro*

Optoelectronics Research Centre, Southampton University, Southampton SO17 1BJ, UK

C. Simonneau, P. Vidakovic, and J. A. Levenson

France Telecom/CNET/DTT/Laboratoire de Bagneux, B.P. 107, F-92225 Bagneux Cedex, France

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We fabricated second-order nonlinear gratings in D-shaped germanosilicate fibers, using thermal poling and periodic electrodes defined by standard photolithography. These gratings, which are up to 75 mm long, were used for efficient quasi-phase-matched frequency doubling of 1.532- μm nanosecond pulses from a high-power erbium-doped fiber amplifier. Average second-harmonic powers as high as 6.8 mW and peak powers greater than 1.2 kW at 766 nm were generated, with average and peak conversion efficiencies as high as 21% and 30%, respectively. © 1999 Optical Society of America

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Since its proposal,¹ researchers have implemented quasi-phase matching (QPM) in many materials and several configurations to achieve efficient nonlinear optical interactions. QPM has several advantages over other traditional techniques (e.g., birefringent and modal phase matching) used to compensate for phase mismatch, induced by dispersion, between electromagnetic fields and corresponding nonlinear driving polarizations in a nonlinear medium. QPM allows one access to new wavelengths, higher efficiencies, and noncritical interaction geometries, and it provides flexibility and new possibilities for phase matching, especially in materials in which the birefringence is not high enough to compensate for the dispersion and in which modal phase matching is not desirable because one wants to avoid generation of light in higher-order modes. For example, the development of electric-field techniques for periodic poling of ferroelectric materials, such as lithium niobate,² has produced a wide range of efficient devices for second-order nonlinear optical frequency conversion in both bulk and waveguide form. Semiconductor³ and polymeric⁴ materials have also been patterned for QPM interactions. However, it is strongly desirable to improve QPM technology and extend it to other nonlinear materials with widespread use in optical applications.

Silica and other glasses are particularly attractive, since they are dominant materials in information technology and in the development of fiber laser sources. These glasses offer high transparency, low cost, a high optical damage threshold, and straightforward integrability; moreover, rare-earth doping of glass fibers has allowed the development of important laser devices, such as erbium-doped fiber amplifiers and, more recently, high-power cw and pulsed fiber lasers. Unfortunately, the inversion symmetry of the glass matrix prevents frequency conversion of coherent radiation through second-order parametric pro-

cesses. The recent discovery that poling techniques⁵ can produce a permanent and large second-order nonlinearity in silica recently made it possible to implement QPM in glass⁶ and glass waveguides and fibers.^{7,8} Periodically poled glass waveguides and fibers are ideal for a wide range of QPM processes, such as frequency conversion of fiber lasers, difference-frequency generation as a means for frequency conversion of telecommunication wavelengths, generation of correlated photon pairs by parametric processes for quantum cryptography, and cascading of second-order nonlinearities to produce equivalent third-order effects (self- and cross-phase modulation) for all-optical switching.

We have already suggested⁷ that, compared with crystal waveguides, periodically poled silica fibers (PPSF's), despite having a lower effective nonlinear coefficient (d_{eff}), can offer a longer interaction length (L) for the same bandwidth and a higher damage intensity threshold (I), thus keeping high values for the efficiency factor $d_{\text{eff}}^2 L^2 I$. In particular, the large value of the bandwidth–interaction length product, owing to low dispersion, makes PPSF suitable for frequency conversion of short pulses (picosecond and even femtosecond) when low group-velocity mismatch between interacting pulses at different frequencies is desirable. In the research reported in Ref. 8 we frequency doubled the output at $\sim 1.5 \mu\text{m}$ from an optical parametric oscillator delivering ~ 100 -fs pulses. The average second-harmonic power and efficiency achieved were limited by the low values of the effective nonlinear coefficient, group-velocity mismatch effects (short interaction length), and higher-order nonlinear effects. It was clear that great improvements could be obtained by optimization of the effective nonlinear coefficient but also that longer pulses of correspondingly narrower spectral bandwidth were needed if we were to use the whole 75-mm grating. In this Letter

we present average second-harmonic (SH) powers and efficiencies as high as 6.8 mW and 21%, respectively, achieved in improved gratings by use as a fundamental source of a high-power erbium-fiber amplifier delivering nanosecond pulses at $\sim 1.5 \mu\text{m}$. To our knowledge the results presented here represent the highest efficiencies achieved in an optical fiber for second-order nonlinear processes and compare well with those obtained by use of periodically poled ferroelectrics.⁹ We believe that they also put PPSF in the position to be considered a serious competitor with other periodically poled materials for frequency conversion of high-peak-power *Q*-switched and mode-locked sources, in particular high-power pulsed fiber lasers,¹⁰ for which an integrated frequency-doubled all-fiber source would be very attractive.

The PPSF samples were fabricated as described in Ref. 7. The D-shaped fiber had a N.A. of 0.191, a core diameter of $6 \mu\text{m}$, an outer diameter of $300 \mu\text{m}$, and an initial flat surface-core distance of $15 \mu\text{m}$. Preliminary etching reduced the flat surface-core distance to $5 \mu\text{m}$, so that after poling the nonlinear layer under the anodic surface included the core region. The patterned aluminum anode (positive electrode during poling) was fabricated on the plane face of the D-shaped fiber by use of standard planar lithography. According to the measurements of the QPM wavelength versus fiber parameters (N.A. and core radius) reported in Ref. 8, periods of 56.45 and $56.5 \mu\text{m}$ were chosen for frequency doubling within the 1530–1540-nm optimum range of tunability of the fundamental fiber amplifier source. Subsequently, the patterned fiber was placed in a high vacuum chamber for thermal poling, which we performed by applying 3–4-kV voltage at 270–280 °C for 10–20 min.

The fundamental source used in the experiment was a diode-seeded erbium-doped amplifier chain based around a large-mode-area doped fiber.¹⁰ The source was seeded by an external cavity laser, which we externally modulated with a fast electro-optic amplitude modulator to produce 5-ns square pulses at a user-definable repetition rate and with a wavelength that could be continuously tuned from 1530 to 1560 nm. The maximum average output power from the amplifier was 100 mW. The pulse energy, peak power, and precise pulse shape were pulse repetition-rate dependent. For the repetition-rate range 1–4 kHz used in these experiments the output pulse duration was 2 ns. The maximum achievable peak power (at 1 kHz) was 30 kW.

To assess the quality of the gratings we initially performed SH measurements in the low-power regime to avoid saturation and higher-order nonlinear effects. Typical QPM curves (SH power versus fundamental wavelength) are shown in Fig. 1 for samples with periods of $56.45 \mu\text{m}$ (sample A) and $56.5 \mu\text{m}$ (sample B). The gratings were 75 mm long for sample A and 60 mm long for sample B. The bandwidths of the QPM curves compare favorably with the expected values for perfect gratings of the same length.

Figure 2 shows the SH power and efficiency as functions of fundamental power for ~ 2 -ns pulses at 4 kHz (inset) at the QPM wavelength of 1531.5 nm. The

maximum average SH power generated in fundamental mode LP_{01} was 6.8 mW with 21% average conversion efficiency. It is evident that there is a roll-off at high power levels with respect to the quadratic behavior (which is linear for the efficiency) at low power levels. This roll-off probably is due to high-order nonlinear effects and is consistent with the experimental observation that at high power levels the SH pulse is of similar duration to the fundamental pulse rather than being shorter (e.g., in the low-depletion regime and assuming Gaussian-shaped pulses, the reduction factor would be $\sqrt{2}$).

To estimate the effective nonlinear coefficient and the peak value of the SH conversion efficiency from Fig. 2 we recall here the time-dependent expression for the conversion efficiency. In a waveguide geometry, in the low fundamental depletion regime and when the walk-off between SH and fundamental pulses is

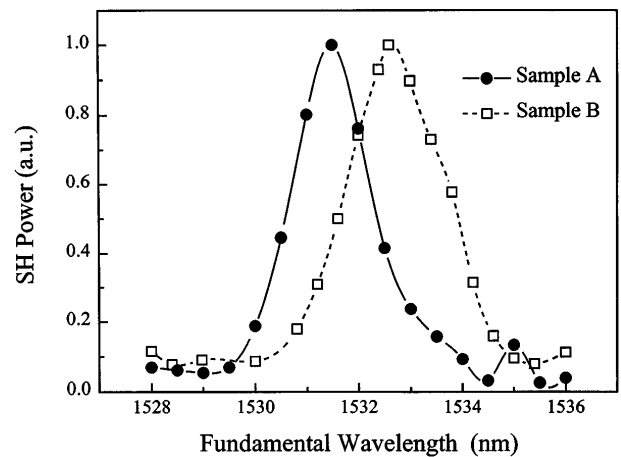


Fig. 1. QPM curves (SH power as a function of fundamental wavelength) for sample A (period, $56.45 \mu\text{m}$; length, 75 mm) and sample B (period, $56.5 \mu\text{m}$; length, 60 mm). The N.A. and the core radius of the fiber are 0.191 and $3 \mu\text{m}$, respectively.

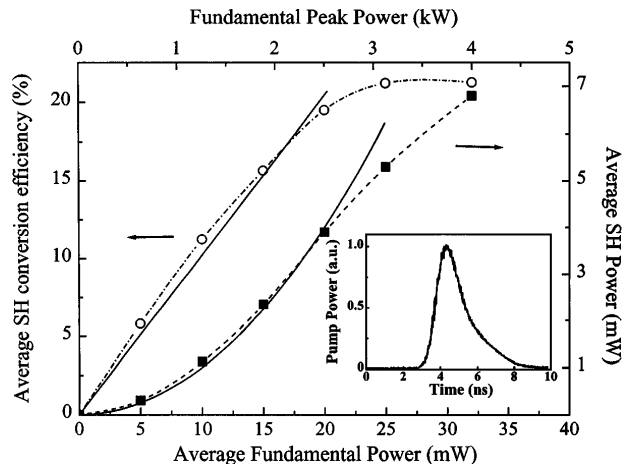


Fig. 2. Average SH power and conversion efficiency as functions of average fundamental power for QPM SH generation of 2-ns pulses at 1531.5 nm and 4 kHz for sample A. Solid curve, quadratic behavior (linear behavior in efficiency) that fits the experimental points at fundamental powers below 20 mW. Inset, fundamental pulse shape.

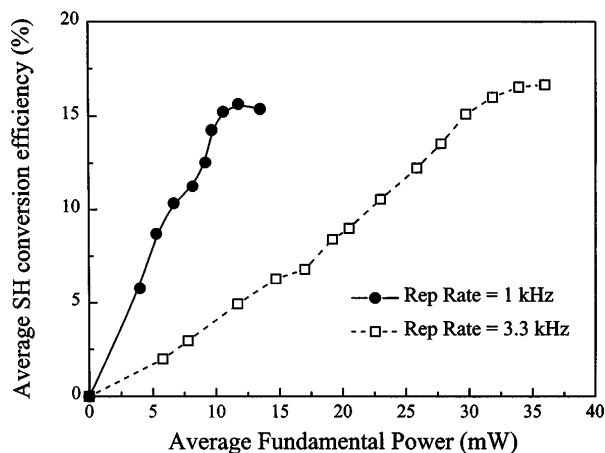


Fig. 3. Average SH conversion efficiency as a function of average fundamental power for the QPM SH generation of 2-ns pulses at 1532.7 nm for sample B at 1 and 3.3 kHz.

negligible, the time-dependent SH conversion efficiency $\eta_{2\omega}(t)$ can be expressed as [x and y are the coordinates perpendicular to the direction of propagation and $f_{\omega}(x, y)$ and $f_{2\omega}(x, y)$ are the normalized fundamental and SH mode profiles, respectively]

$$\eta_{2\omega}(t) = \frac{2\omega^2 d_{\text{eff}}^2}{n_{2\omega} n_{\omega}^2 \epsilon_0 c_0^3} \frac{P_{\omega}(t)}{A_{\text{OVL}}} L^2 \text{sinc}^2\left(\frac{\Delta\beta L}{2}\right),$$

$$d_{\text{eff}} = \frac{1}{m\pi} \frac{|\int \int f_{\omega}^2(x, y) d(x, y) f_{2\omega}^*(x, y) \delta x \delta y|}{|\int \int f_{\omega}^2(x, y) f_{2\omega}^*(x, y) \delta x \delta y|},$$

$$A_{\text{OVL}} = \frac{1}{|\int \int f_{\omega}^2(x, y) f_{2\omega}^*(x, y) \delta x \delta y|^2}, \quad (1)$$

where ω is the fundamental frequency, $P_{\omega}(t)$ is the time-dependent fundamental power, $d(x, y)$ is the spatial distribution of the nonlinear coefficient (along the direction of propagation z the nonlinear coefficient is supposed to be ± 0 modulated), d_{eff} is the effective nonlinear coefficient that depends on the m th QPM order and includes the overlap between poled region and the interacting modes, L is the grating length, $n_{2\omega}$ and n_{ω} are the effective refractive indices at frequencies 2ω and ω , respectively, ϵ_0 is the dielectric constant in vacuum, c_0 is the speed of light in vacuum, A_{OVL} is an equivalent area that depends on the overlap integral between the interacting fields, and $\Delta\beta = \Delta\beta(\omega) = 2(\omega/c_0)(n_{2\omega} - n_{\omega})$ is the wave-vector mismatch. From the detailed pulse-shape data obtained at the 20-mW average fundamental power data point shown in Fig. 1 (where the behavior is still linear in efficiency), and by averaging the conversion efficiency over the pulse shape, we estimate d_{eff} to be 0.014 pm/V for sample A. Correspondingly, we also estimate that efficiencies exceeding 30% were achieved at the peak of the pulse for peak fundamental powers of ~ 2.5 kW.

Figure 3 shows the conversion efficiency versus pump power for the second shorter grating ($L = 6$ cm), sample B, at the QPM wavelength of 1532.7 nm for two different repetition rates. From these curves, and using Eq. (1), up to the point at which the quadratic behavior is maintained, one can estimate that peak

SH powers exceeding 1.2 kW were generated for ~ 4.5 -kW peak fundamental power. These data and those shown in Fig. 1 for grating A indicate that the two samples have approximately the same effective nonlinearity, highlighting the reproducibility of our poling process.

In conclusion, we have reported efficient frequency doubling of 1532-nm radiation in an all-fiber system based on a high-power fiber amplifier and a periodically poled silica fiber. The efficiencies and the second-harmonic powers obtained suggest that PPSF is a mature medium for frequency conversion of high-power laser sources, in particular, fiber lasers. The nonlinear grating and the effective nonlinear coefficient are still far from optimum (it is estimated that d_{eff} can be improved 4–6 times in such a fiber), and further improvements, including in fiber design and poling optimization, will reduce the power levels necessary for useful conversion efficiencies. Other wavelength ranges (e.g., doubling of 0.8–1- μm sources) and other second-order processes (e.g., difference-frequency generation and parametric downconversion) will be the subject of further experiments.

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*Present address, Corning, Fontainebleau Research Centre, Avon, France.

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